

# **Determination of Vertical Refractivity Structure from Ground-based GPS Observations**

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## **LONG-TERM GOAL**

The goal is to develop GPS remote sensing techniques for the determination of atmospheric signal delay, refractive bending, and refractivity structure to aid in sensing of the refractive environment of ships or land-based stations.

## **SCIENTIFIC OBJECTIVES**

The primary scientific objective of this research is to develop GPS sounding techniques for ground based atmospheric refractivity sensing. Atmospheric profiling with GPS from space has been demonstrated (e.g. Rocken *et al.*, 1997). Ground based receivers have been used to determine integrated atmospheric water vapor above a site, but profiling techniques with ground-based GPS observations are still under development (Anderson 1982, 1994). Ground based observations of GPS tropospheric signal delay and bending cannot be inverted to high-resolution atmospheric profiles comparable to radiosondes, but they provide direct measurements of microwave signal bending (Sokolovskiy *et al.*, 2001) and coarse refractivity structure information (Lowry *et al.*, 2001).

## **APPROACH**

We are pursuing a three-step approach to reach the long-term goal of refractivity profiling with GPS from a ship.

- (1) Develop and test GPS single slant measurement techniques
- (2) Develop techniques to interpret these slant measurements
  - (a) Determination of profile information & signal bending
- (3) Develop a system for a mobile platform
  - (a) Evaluation and development of precise kinematic positioning
  - (b) Field tests – Flip-ship (FLIP) experiment
  - (c) Ocean ship-board experiment

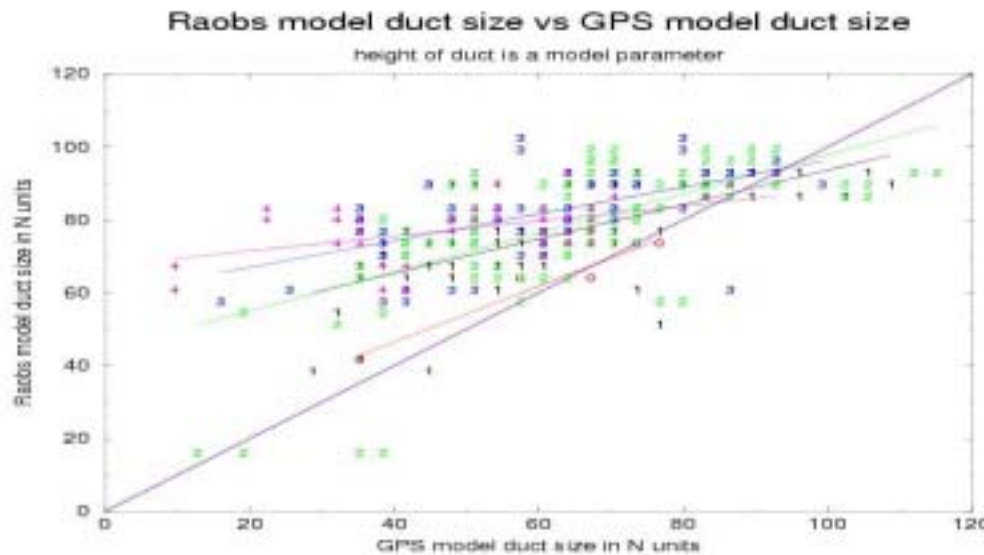
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During the last year significant effort was invested in finalizing and revising several 2001 publications on this ONR-funded research project. The development and test of slant measurement techniques has led to several new publications (Braun *et al.*, 2001, Rocken *et al.*, 2001a, Sokolovskiy, *et al.*, 2001a,b, Lowry *et al.*, 2001). The techniques developed for (1) and (2) were tested with additional data sets collected in California, and Colorado. We have also begun to accumulate statistics on the performance of the techniques. The focus of our research during the last year has shifted to (3). Software was developed for pre-processing of low elevation data and for kinematic point positioning processing of GPS data. We investigated the impact of kinematic position errors on the profiling. We purchased new GPS receivers for higher reliability tracking at low elevations. A first ocean experiment has been conducted aboard FLIP.

## WORK COMPLETED

Progress was made in (1) testing and modifying the GPS profiling technique; (2) comparison of kinematic precise point positioning solutions with differential baseline solutions for data collected on an ocean buoy; (3) development of software for processing data from mobile sites; (4) new software development for preprocessing low-elevation observations; (5) preparation for and participation in ocean experiment off Hawaii; (6) evaluation of a new processing technique for the detection of ducting conditions from space. The main accomplished tasks are summarized below:

- **We have tested the previously developed profiling and bending angle techniques** with additional data collected at Point Loma. We also applied slight modifications to the search space for the 2-parameter model, restricting the possible height for the onset of an ocean duct to 300 m. Results comparing the duct width as determined from the radiosondes to the GPS-estimated ducts show a strong correlation between the two techniques. This confirms previous conclusions that GPS can

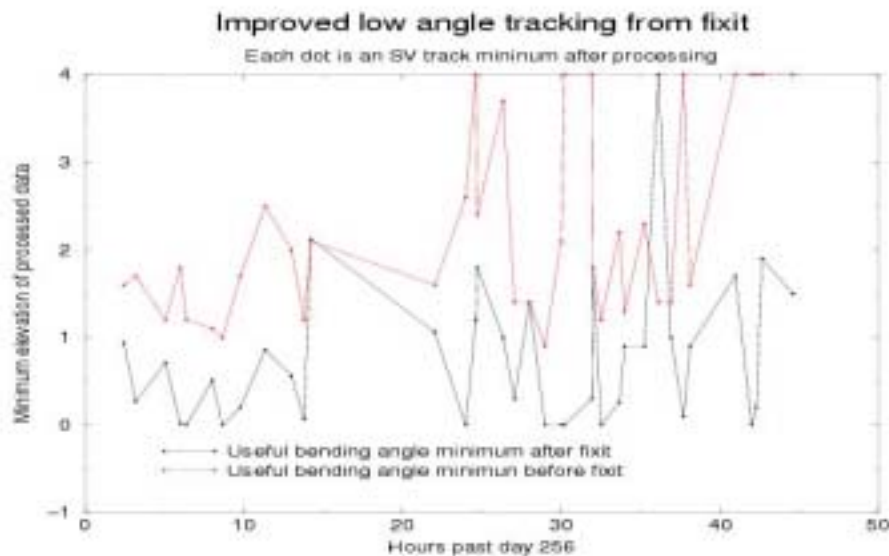


*Figure 1 shows the GPS-determined duct size vs. the radiosonde measured duct size. The numbers and colors plotted represent the minimum elevation angle to which GPS data were tracked and used in the inversion. It can be seen that the GPS determined ducts generally agree better with the radiosonde ducts when lower elevation tracking data are available. Unfortunately only very few cases with 0-degree tracking are available. This result re-emphasizes the importance of reliable GPS tracking to low elevations.*

be used for duct detection. However, while GPS can provide an indication for the existence and strength of a duct it cannot provide high-resolution profile information.

•**We compared precise kinematic point position solutions** with GPS data collected on an ocean buoy with differential kinematic solutions. Differential kinematic solutions for this case (the buoy is only about 2 km offshore from a reference site) are considered correct at the several-cm level. Precise kinematic point positioning, while less precise is the only positioning technique applicable on a ship in the open ocean. The difference between the two kinematic solutions is attributed primarily to errors in precise kinematic point positioning. Since the GPS profiling and bending determination are affected by velocity errors we investigated the differential velocity between the two kinematic solutions. We concluded that kinematic point positioning can be used to achieve velocities of better than 1 mm/sec.

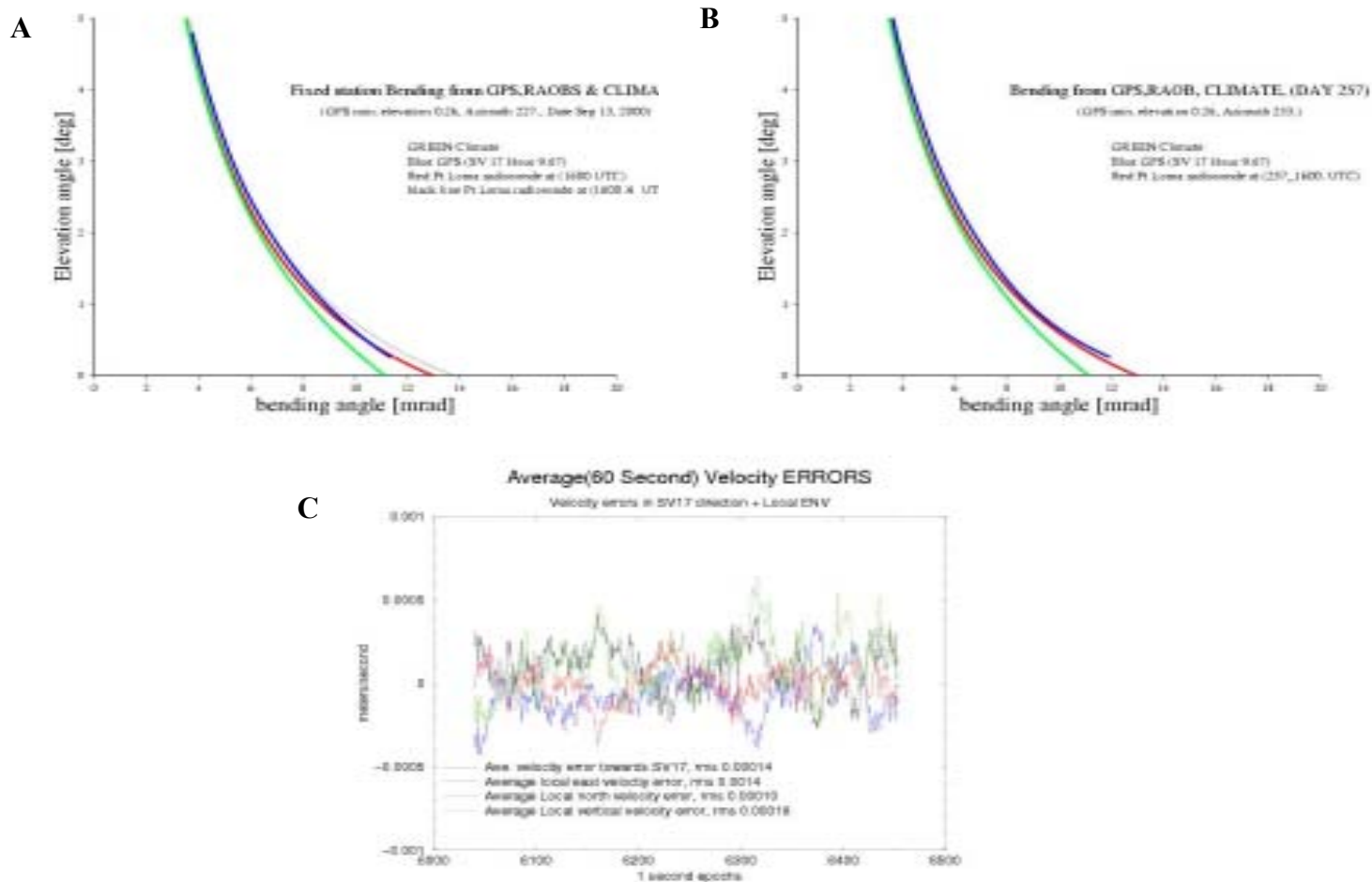
•**We developed a new pre-processing program for low elevation data.** Preprocessing of the data is required to repair frequent cycle slips. For low elevation observations the rate of change in the measured phase due to the atmospheric delay is high, multipath interference is high, the signal strength is low, and the data have frequent gaps. To achieve cycle slip repair of such a problematic data a new program called “FIXIT” was developed. FIXIT works on undifferenced data from a single site. Because FIXIT computes a low order spline regression fit to the time derivative of the observations and extrapolates this fit in time to fix cycle slips across data gaps, it works best if the motion of the GPS antenna has only small accelerations and the sampling rate is high. The program was designed to work with data from static sites or large ships. Preprocessing of data from platforms with strong accelerations such as ocean buoys or automobiles is difficult with FIXIT. The main benefit of this program is that we are able to process data to lower tracking angles.



**Figure 2 Bending angle profiles can only be computed to the lowest angle to which GPS data are available. This plot shows the impact that the use of FIXIT had on days 256 and 257, 2000, extending the available data to lower elevation angles.**

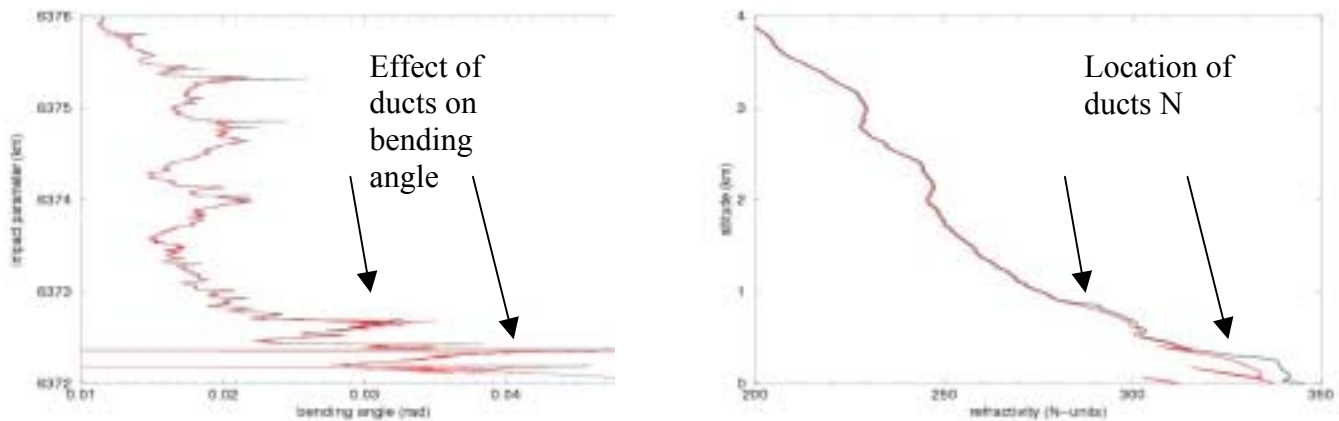
•**We participated in the Rough Evaporation Duct (RED) experiment.** In preparation for RED we purchased two Trimble 4500 GPS receivers. These receivers had demonstrated good low-elevation tracking behavior (fewer cycle slips than some of the other receivers that were considered for RED) in tests conducted in Boulder. We packaged the receivers in a rack-mount, designed the antenna mounts for the FLIP ship, and developed the data collection system for the experiment. Kenn Anderson handled the actual installation on FLIP. We collected data on FLIP off-shore Oahu, Hawaii, Sept. 5 2001 – Sept. 14 2001. Unfortunately it was not possible to test the system prior to deployment for the experiment. Since the experiment has just ended (on Sept. 15, 2001) we do not yet have any photos of the instruments during the experiment or final results. We do however have the GPS data. An initial investigation of the data reveals that the data from FLIP are significantly noisier than data collected with the same receivers in Boulder. We are still trying to understand the reasons for this increase in noise. Clearly there were significant obstructions on FLIP that affect the GPS data quality, the multipath environment of FLIP is bad for GPS reception, and finally the motion of FLIP appears to have higher accelerations than we had anticipated.

•**We investigated the effect of kinematic point positioning on the profiling and ducting results.**



**Figure 3** Signal bending angle from GPS, climatology, and radiosondes for static (a) and kinematic (b) analysis cases. The lower panel (Cc) shows the velocity error due to kinematic point positioning of the fixed Point Loma site. These velocity errors have negligible impact on the profiles. This was done in two steps. (A) We determined the position of a site with kinematic point positioning, using the Bernese GPS software and IGS GPS satellite orbits and GPS clock solutions. (B) The point position solutions were then used (instead of the known fixed position) to compute the excess phase. The excess phase data were inverted to extract atmospheric profiling and bending information. The figures below show that, in spite of the added phase error due to kinematic precise point positioning, the profile and signal bending can be determined quite reliably. The plots show (a) the bending angle determined when the position is held fixed to its true position, (c) the velocity error due to kinematic point positioning, (b) the bending angle after the kinematic point position is used.

•**We investigated the feasibility of ocean duct detection from space.** New algorithms for the simulation and inversion of space based occultation data were developed (primarily with independent funding from the National Science Foundation). Based on a high-resolution radiosonde profile collected at Point Loma by Kenn Anderson we simulated and inverted occultation data that would be received by a GPS receiver in low earth orbit. The results of this test are shown below. The new processing technique (called Canonic Transform technique) clearly shows spikes in the bending angle profiles. Spikes in the retrieved refractivity also indicate the possibility of resolving layers of ocean ducting with the occultation method. We plan to look for this phenomenon in real occultation data from the currently operating CHAMP and SAC-C satellite mission.



**Figure 4 shows in red the simulated GPS data for bending (left panel) and for the refractivity profile (right panel), and in black the “truth” data computed from the Point Loma radiosonde. While GPS cannot fully resolve the ducts in refractivity the ducting features can clearly be seen in the corresponding bending angle profile.**

## IMPACT/APPLICATION

Remote sensing of atmospheric features and refractivity profiles with GPS promises to impact Navy communication and sensing capabilities and to provide a new data set for improved numerical weather prediction. Ground based determination of bending angles using GPS has the potential for aiding in locating exo-atmospheric targets. Precise kinematic point positioning to conduct these activities from a moving platform (ship) seems feasible and may also lead to precise timing on ships. The mapping function as well as the zero difference to double difference inversion technique developed earlier during this effort have many applications in high accuracy GPS geodesy, ionospheric modeling, and meteorology.

## RELATED PROJECTS

- 1) Dr. Kenn Anderson is developing techniques that use amplitude measurements for the detection of specific refractivity profiles. Dr. Anderson's amplitude approach and the phase approach described here may work best in combination.
- 2) The Department of Energy is continuing to fund UCAR to develop low-cost L1-only GPS systems for tropospheric tomography. This study requires the measurement of single transmitter - receiver slant ranges, the same GPS observable required for refractivity profiling.
- 3) NCAR and NOAA scientists are working on assimilation of single GPS slant measurements into numerical weather models. The slant measurement techniques that we are developing with this study can then be applied to numerical weather forecasting.
- 4) We have begun the process of filing a joint patent with Georgia Tech on the GPS bending technique,

## SUMMARY

Results so far can be summarized as: (1) Coarse refractivity profile information can be obtained from ground GPS; (2) Good bending information can be obtained; (3) Application from a mobile platform appears feasible – the errors due to kinematic positioning do not prevent duct detection and bending angle determination; (4) Several peer-reviewed papers have been published and a joint patent with GATech is planned. GPS data collected during RED experiment have to be processed next. Ocean going application of the technique has to be demonstrated. The main challenge remains to obtain high-quality GPS data at very low observation angles.

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